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Role of zinc enriched manures in enhancing yield and quality of maize (*Zea mays*) grown in zinc deficient calcareous soil

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ABSTRACT

The present study was carried out during 2020–21 and 2021–22 at Agricultural College and Research Institute, Tamil Nadu to investigate the influence of various Zn sources [inorganic ($ZnSO_4$ and Zn-EDTA), enriched organic manure (vermicompost + $ZnSO_4$ and farm yard manure (FYM) + $ZnSO_4$), and Zn solubilizing bacteria (ZSB)) (with and without $ZnSO_4$)] on maize (*Zea mays* L.) growth and Zn accumulation in grain. The experiment was laid out in a randomized block design (RBD) with three replications taking maize hybrid variety i.e. Monsanto Dekalb as a test crop. Simultaneously, an incubation study with similar Zn sources was run to study the Zn release patterns for 10-weeks. The incubation experiment showed the total DTPA extractable Zn release over 10-weeks was significantly higher in $ZnSO_4$ enriched vermicompost (ER–I) (94.5 mg/kg) than in the other Zn sources. The use of vermicompost enriched with $ZnSO_4$, in combination with the recommended dose of fertilizers (RDF), noticeably increased grain yield to the tune of 8264 kg/ha when compared to other treatments. Additionally, this treatment significantly boosted Zn accumulation in grains and enhanced Zn availability in the soil, which surpassed all other treatments. Consequently, these findings underscore the pivotal role of Zn enriched vermicompost in facilitating Zn bio-fortification in maize crops grown in Zn deficient calcareous soil.

Keywords: Bio-fortification, Calcareous soil, Enriched manures, Vermicompost

Zinc (Zn) is the fourth most important yield limiting nutrient in agricultural crops. In India, ~72.2 Mha of cultivated soils are classified as Zn deficient (Shukla *et al.* 2021). Worldwide, around 49% of arable land area shows a decrease in crop yield because of Zn inadequacy (Hacisalihoglu 2020). Zinc is a trace mineral essential for all forms of life (Cabot *et al.* 2019). Commonly zinc sulphate ($ZnSO_4.7H_2O$) is used to correct the deficiency of Zn. Such conventional fertilizers have very low use efficiency hovering around 2–5% (Dimkpa *et al.* 2020). But organically chelated Zn (Zn enriched organic manures), supplies a substantial amount of Zn to the plants with less interaction with soil components (Thiyagarajan 2021). It is evident from previous studies that Zn enriched organic manure addition contributes to higher crop yield and nutrient uptake (Prathap *et al.* 2022, Pradhan *et al.* 2025). Therefore, the application of Zn through organic manures could be a feasible and environmental friendly solution to remediate Zn deficiency in soils and enhance quality crop production. Maize (*Zea mays* L.) is one of the most important cereals, next to wheat and rice in the world, which can be grown under diverse environmental conditions (Dash *et al.* 2023, Dash *et al.* 2024, Dash *et al.* 2025). Maize is particularly sensitive to Zn deficiency (Amit 2020, Raza *et al.* 2024, Yadav *et al.* 2024). Liu *et al.* (2020) had reported an increase in maize grain yield to the extent of 4.2–16.7%. Therefore, it is hypothesized that the application of Zn fertilizer in combination with organic manures can effectively mitigate Zn deficiency in soils and also ensure that crops receive an adequate supply of this micronutrient. This, in turn, promotes healthier plant growth, improved crop yields, and enhanced nutritional content in the harvested produce. To test the hypothesis, this study was framed, to assess the releasing pattern of Zn with Zn enriched organic manures during the incubation study; to evaluate the effect of Zn enriched organic manures on the growth and yield attributes, nutrient uptake, quality parameters of maize and soil available nutrient status in the Zn deficient calcareous soil.

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MATERIALS AND METHODS

Experiment site: The present study was carried out during 2020–21 and 2021–22 at Agricultural College and Research Institute (10°3' and 10°48'N latitude and 77°15' and 78°20' E longitude), Tamil Nadu. The experiment consisted of nine different treatment [T_1, Recommended dose of fertilizer (RDF) (N:P:K @ 250:33:62.5 kg/ha) (Control); T_2, RDF + Basal application of $ZnSO_4$ @37.5 kg/ha (RDF + $ZnSO_4$); T_3, RDF + Basal application of Zn-EDTA @5 kg/ha (RDF + Zn–EDTA); T_4, RDF + Zn solubilizing bacteria @2 kg/ha (RDF + ZSB); T_5, RDF + $ZnSO_4$ @37.5 kg/ha + Zn solubilizing bacteria @2 kg/ha (RDF + $ZnSO_4$ + ZSB); T_6-RDF + $ZnSO_4$ @37.5 kg incubated with 375 kg vermicompost for 30 days (1:10 ratio) (RDF + $ZnSO_4$ + Vermicompost); T_7, RDF + $ZnSO_4$ @37.5 kg incubated with 375 kg FYM for 30 days (1:10 ratio) (RDF + $ZnSO_4$ + FYM); T_8, RDF + 0.5% $ZnSO_4$ foliar spray thrice at knee high stage, tasseling and cob initiation stage (RDF + $ZnSO_4$ FS); T_9, RDF + 0.2% Zn EDTA foliar spray thrice at knee high stage, tasseling and cob initiation stage (RDF + Zn EDTA FS)]. The experiment was laid out in a randomized block design (RBD) with three replications taking maize hybrid variety, i.e. Monsanto Dekalb as a test crop. A plot size of 5 m × 4 m (20 m^2) was adopted with a buffer channel around each plot for irrigation.

Treatment details for zinc release pattern study: To study the Zn release pattern, soil samples with a previous history of Zn deficiency, were collected from the farm of Agricultural College and Research Institute, Tamil Nadu in 2020–21. An incubation experiment was conducted on this Zn deficient soil having treatments; T_1, $ZnSO_4$ @18.75 mg/kg; T_2, Zn EDTA @2.5 mg/kg; T_3, ZSB @1 mg/kg; T_4, $ZnSO_4$ @18.75 mg/kg + ZSB @1 mg/kg; T_5, Enriched compost-I (ER-I) @5 g/kg and T_6, Enriched compost-II (ER-II) @5 g/kg at 28±0.5 ºC for 10 weeks. The enriched organic compost was prepared by mixing 37.5 kg of $ZnSO_4.7H_2O$ (from here on denoted as $ZnSO_4$) with 375 kg each of vermicompost (Enriched compost-I) and farm yard manure (Enriched compost-II), respectively in a plastic container and keeping undisturbed under shade at 60% moisture content. The treatments were replicated thrice in a completely randomized design (CRD). The soil samples were collected at weekly intervals and analyzed for the DTPA extractable Zn content (Lindsay and Norvell 1978).

Soil sample analysis: The soil samples were drawn from the experimental sites and analyzed during the different growth stages of the maize crop (30 DAS, 60 DAS, and after harvest of the crop). The DTPA extractable Zn was analyzed by following the protocol of Lindsay and Norvell (1978).

Recording of plant growth attributes and nutrient content: In the net plot area, five plants were selected randomly and tagged for recording the biometric observations, viz. cob length (cm), cob weight (g), number of grains cob-1, and test weight (weight of 100 filled grains at 14% moisture). The samples were shade-dried, followed by oven-drying at 65°C to analyse total Zn. The grain samples were collected from each treatment and analyzed for total Zn. The starch (Hodge and Hofreiter 1962) and crude protein (Thiex 2009) contents were also assessed in the samples.

Statistical Analysis: The data were statistically analyzed as suggested by Gomez and Gomez (1984). Wherever the treatment differences were found significant, critical differences were worked out at 5% probability level and values were furnished.

RESULTS AND DISCUSSION

Effect of different Zn source and organic manures on yield attributes of maize: A significantly higher cob length (20 cm) and cob weight (204.0 g) were observed in the plants treated with RDF + $ZnSO_4$ + Vermicompost (Table 1). This notable enhancement can be attributed to the synergistic supply of nutrients from multiple sources, with vermicompost contributing significantly due to its rich nutrient content. The stimulation of enzymatic activities and auxin metabolism in plants due to Zn application played a crucial role in augmenting both cob length and weight (Dubey *et al.* 2021). The seed index (weight of 100-seeds) of the maize crop was in the range of 34.2–39 across the treatments. The enriched compost concoctions with $ZnSO_4$, viz. RDF + $ZnSO_4$ + Vermicompost (39.0 g) and RDF + $ZnSO_4$ + FYM (38.9 g), showed significantly higher seed index values compared to other treatments. In fact, the treatments showed similar trends concerning number of grains/cob, with the highest values in RDF + $ZnSO_4$ + Vermicompost (535.8) (Table 1). The application of Zn fertilizer along with organic manure such as vermicompost or FYM was found to positively impact maize growth. In a two-year consecutive experiment, the application of 25 kg/ha of soil-applied Zn resulted in increased cob length, cob weight, grains/cob, and cob girth (Takrattanasaran *et al.* 2013).

Effect of Zn enriched organic manures on grain yield and quality: The grain yield of maize crops ranged from 6865.3–8264.0 kg/ha. Significantly higher grain yield was noticed in RDF + $ZnSO_4$ + Vermicompost (Table 1). These findings corroborate the study by Kumar *et al.* (2022), which indicated that the combined use of integrated rock phosphate and Zn in vermicompost, resulted in superior maize yields compared to vermicompost applied without rock phosphate and Zn. The crude protein content of maize ranged between 9.2–11.1%. The crude protein content was significantly higher in maize plants of RDF + $ZnSO_4$ + Vermicompost which was at par with plants of RDF + $ZnSO_4$ + FYM (Table 2). Because, Zn helps in the uptake and assimilation of nitrogen, which is a primary component of amino acids and proteins. It regulates glutamate dehydrogenase, glutamine synthetase, and nitrate reductase enzymes, promoting nitrogen assimilation into amino acids and increasing protein content (Sun *et al.* 2020). Zinc plays a crucial role in protein metabolism by ensuring the stability and function of genetic material (Singh *et al.* 2005). It is essential for chromatin structure, and DNA or RNA metabolism. Zn deficiency leads to RNA degradation, reduced RNA polymerase activity, ribosomal deformation,

Table 1 Effect of different Zn sources and organic manures on yield attributes, yield and quality of maize (mean data of years 2020–21 and 2021–22)

Treatment	Cob length (cm)	Cob weight (g)	Seed index (g)	No. of grains/cob	Grain yield (kg/ha)	Stover yield (kg/ha)	Starch (%)	Crude protein (%)
T_1	17.9^{c}	170^{f}	35.4^{bc}	432^{d}	6865^{g}	8260^{g}	55.3	9.20^{d}
T_2	18.7^{bc}	182^{cd}	34.2^{c}	455^{c}	7519^{d}	9254^{e}	55.4	10.3^{bc}
T_3	19.2^{ab}	191^{b}	35.8^{bc}	497^{b}	7750^{c}	9859^{c}	55.3	10.1^{bc}
T_4	18.2^{c}	173^{ef}	35.7^{bc}	402^{e}	7025^{f}	8688^{f}	55.3	10.0^{c}
T_5	19.2^{ab}	188^{bc}	36.3^{b}	483^{b}	7595^{d}	9750^{c}	55.4	10.5^{b}
T_6	20.0^{a}	204^{a}	39.0^{a}	535^{a}	8264^{a}	10760^{a}	55.4	11.1^{a}
T_7	19.8^{a}	202^{a}	38.9^{a}	525^{a}	8070^{b}	10200^{b}	55.4	11.0^{a}
T_8	18.5^{bc}	179de	35.2^{bc}	440^{cd}	7200^{e}	9459^{d}	55.3	10.1^{c}
T_9	18.6^{bc}	181^{d}	35.3^{bc}	447^{cd}	7290^{e}	9524^{d}	55.3	10.4^{bc}
LSD (p=0.05)	0.84	6.8	1.8	17	139	149	NS	0.40

T_1, RDF ($N:P_2O_5:K_2O$ @ 250:75:75 kg/ha) (Control); T_2, RDF+ Basal application of $ZnSO_4$ @37.5 kg/ha; T_3, RDF + Basal application of Zn–EDTA @5 kg/ha; T_4, RDF+Zn solubilizing bacteria @2 kg/ha; T_5, RDF+$ZnSO_4$ @37.5 kg/ha+Zn solubilizing bacteria @2 kg/ha; T_6, RDF+$ZnSO_4$ @37.5 kg incubated with 375 kg vermicompost for 30 days (1:10 ratio); T_7, RDF+ $ZnSO_4$ @37.5 kg incubated with 375 kg FYM for 30 days (1:10 ratio); T_8, RDF+Foliar spray of $ZnSO_4$ @0.5% three times at knee high stage, tasseling and cob initiation stage and T_9, RDF+ Foliar spray of Zn EDTA @0.2% three times at knee high stage, tasselling and cob initiation stage; RDF, Recommended dose of fertilizer.

Table 2 Effect of the application of different Zn sources and organic manures on Zn uptake by maize crop and DTPA extractable Zn content at different crop growth stages (mean data of years 2020–21 and 2021–22)

Treatment	Zn uptake in plants (g/ha)				Available zinc in soil (g/ha)		
	30 DAS	60 DAS	Grain	Stover	30 DAS	60 DAS	Post- harvest
T_1	39.2^{i}	162^{h}	167^{h}	118^{g}	0.7^{f}	0.6^{g}	0.4^{g}
T_2	67.4^{e}	292^{e}	219^{f}	174^{e}	1.1^{c}	1.0^{d}	0.9^{d}
T_3	80.0^{c}	361^{c}	304^{c}	232^{c}	1.4^{b}	1.2^{c}	1.05^{b}
T_4	45.8^{h}	213^{g}	184^{g}	143^{f}	0.8^{e}	0.7^{f}	0.6^{f}
T_5	72.6^{d}	309^{d}	246^{e}	198^{d}	1.1^{c}	1.0^{d}	0.9^{c}
T_6	103.1^{a}	459^{a}	407^{a}	323^{a}	1.7^{a}	1.5^{a}	1.3^{a}
T_7	95.9^{b}	420^{b}	367^{b}	278^{b}	1.6^{a}	1.4^{b}	1.3^{a}
T_8	54.8^{g}	266^{f}	254^{e}	179^{e}	0.9^{d}	0.9^{e}	0.8^{e}
T_9	59.9^{f}	310^{d}	270^{d}	203^{d}	1.0^{d}	0.9^{e}	0.8^{e}
CD (p=0.05)	2.7	15.9	12.6	5.9	0.05	0.05	0.05

T_1, RDF ($N:P_2O_5:K_2O$ @ 250:75:75 kg/ha) (Control); T_2, RDF+ Basal application of $ZnSO_4$ @37.5 kg/ha; T_3, RDF + Basal application of Zn–EDTA @5 kg/ha; T_4, RDF+Zn solubilizing bacteria @2 kg/ha; T_5, RDF+$ZnSO_4$ @37.5 kg/ha+Zn solubilizing bacteria @2 kg/ha; T_6, RDF+$ZnSO_4$ @37.5 kg incubated with 375 kg vermicompost for 30 days (1:10 ratio); T_7, RDF+ $ZnSO_4$ @37.5 kg incubated with 375 kg FYM for 30 days (1:10 ratio); T_8, RDF+Foliar spray of $ZnSO_4$ @0.5% three times at knee high stage, tasseling and cob initiation stage and T_9, RDF+ Foliar spray of Zn EDTA @0.2% three times at knee high stage, tasselling and cob initiation stage; RDF, Recommended dose of fertilizer.

and a decline in ribosome numbers, ultimately inhibiting protein synthesis (Sadeghzadeh 2013). Roy *et al.* (2014) similarly reported a 26.9% increase in seed crude protein content in green grams due to Zn fertilization.

Effect of the application of different Zn sources and organic manures on Zn uptake and its soil availability at different stages of maize growth: The highest Zn accumulation in grain (407.7 g/ha) was observed in the RDF + $ZnSO_4$ + Vermicompost treatment (Table 2). This can be attributed to the enhanced Zn availability in calcareous soils, which are inherently Zn deficient. Among the different Zn application methods, the combination of Zn with vermicompost proved to be the most effective. The application of vermicompost significantly increased soil organic matter content (Oyege and Balaji Bhaskar 2023), which played a crucial role in Zn availability. Higher organic matter promotes the formation of organic chelates, which bind with Zn to form soluble complexes that plants can efficiently absorb. Shuman (1988) also reported improved Zn availability in soils with higher organic matter content. Additionally, vermicompost application improves soil physicochemical properties, reducing nutrient loss through leaching (Chatterjee *et*

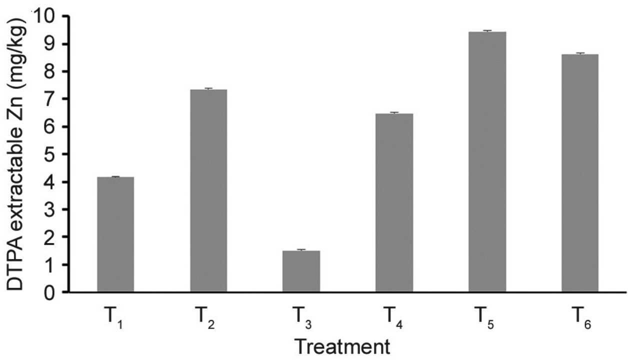

Fig. 1 Effect of different treatments on average DTPA extractable Zn content in soil the end of incubation period.
T_1, $ZnSO_4$ @18.75 mg/kg; T_2, Zn EDTA @ 2.5 mg/kg; T_3, ZSB @1 mg/kg; T_4, $ZnSO_4$ @18.75 mg/kg + ZSB @1 mg/kg; T_5, Enriched compost–I (ER–I) @5 g/kg and T_6, Enriched compost–II (ER–II) @5 g/kg at 28 ± 0.5ºC for 10 weeks.

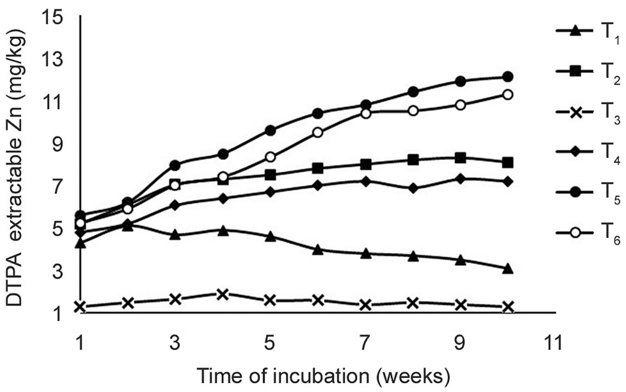

Fig. 2 Interactive effect of different treatments and period of incubation on DTPA extractable Zn content in soil.
T_1, $ZnSO_4$ @18.75 mg/kg; T_2, Zn EDTA @2.5 mg/kg; T_3, ZSB @1 mg/kg; T_4, $ZnSO_4$ @18.75 mg/kg + ZSB @1 mg/kg; T_5, Enriched compost-I (ER–I) @5 g/kg, and T_6, Enriched compost–II (ER-II) @5 g/kg at 28 ± 0.5ºC for 10 weeks.

al. 2020). It stimulates soil microorganisms to produce polysaccharides, which enhance soil structure, porosity, and water retention. This, in turn, ensures better Zn availability to maize plants. However, despite these benefits, the soluble Zn organic complexes formed in soil are susceptible to leaching into groundwater, potentially leading to water pollution. Furthermore, excessive Zn uptake by plants may result in the deficiency of other essential nutrients, such as Ca, Fe, and Cu (Prasad *et al.* 2016).

The lowest Zn accumulation in grain was found in maize plants of control plots. Our result corroborated with the result observed by Singh *et al.* (1983). They suggested that the beneficial effects of organic manures were due to the presence of chelating agents such as fulvic acid, which could increase the mobility of Zn from straw to grain. This is consistent with our results, where the Zn content in the grains is significantly higher than in the stover. There was a decreasing trend of soil available Zn starting from 30–60 DAS to post-harvest irrespective of treatments (Table 2). This decline may be attributed to the continuous removal of Zn by the crop and various transformations occurring in the soil. The Zn-enriched vermicompost exhibited the highest soil available Zn at 30 and 60 DAS, which was consistent with Singh *et al.* (1983), who reported increased Zn availability in soil when $ZnSO_4$ was applied alongside organic manures. Another factor responsible for soil available Zn high could be the increase in labile soil organic carbon resulting from vermicompost application, which mineralizes at a faster rate, elevating nutrient concentrations in soil solution, including micronutrients (Dash *et al.* 2023).

Zinc release pattern in soil: The results showed that the Enriched Compost-I @5 g/kg (T_5) showed the highest average DTPA extractable Zn (9.44 mg/kg) in soil compared to other treatments (Fig. 1). This was significantly higher than that found in Enriched Compost-II @5 g/kg (T_5). The average DTPA extractable Zn content from different fertilizer sources followed the order $T_5>T_6>T_4>T_2>T_1>T_3$. The total DTPA extractable Zn release throughout incubation was the highest for ER-I (94.5 mg/kg) as compared to the rest of the Zn sources (Fig. 2). This could be attributed to the higher solubility of $ZnSO_4$ and the subsequent conversion of fixed Zn ($ZnSO_4$ transformed into zinc carbonate, $ZnCO_3$) in the calcareous soil, due to the acids produced during the decomposition of vermicompost. Our findings align with the results reported by Motaghian and Hosseinpur (2017), which indicated a significant increase in DTPA-extractable Zn in soils amended with 0.5% and 1% vermicompost and cow manure when compared to unamended soil.

Thus, it was concluded that a combination of zinc (Zn) and organic manure is effective in addressing Zn deficiency in plants while simultaneously increasing Zn accumulation in maize grains. The application of 37.5 kg of $ZnSO_4$, when combined with a soil application of 375 kg of vermicompost, along with the recommended dose of fertilizer, has notably improved the availability of Zn in the soil. Consequently, maize plants were able to uptake an appropriate quantity of Zn from the soil, resulting in enhanced Zn content in both the grains and overall plant growth and yield, all achieved sustainably. The Zn enriched vermicompost should be adopted as an integrated Zn management strategy for maize grown in Zn deficient calcareous soil. So, the optimal application rate is 37.5 kg $ZnSO_4$ + 375 kg vermicompost, supplemented with the recommended fertilizer dosage. In cases where vermicompost is not readily available, farmyard manure can serve as an alternative source of organic manure, albeit with slightly lower efficiency compared to vermicompost.

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